On Using Cooperative Routing for Lifetime Optimization of Multi-Hop Wireless Sensor Networks: Analysis and Guidelines

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***Abstract*—Theoretically optimal performance and behavior of a routing protocol are very important because they can be used to guide the design of practical protocols. Motivated by the promising lifetime performance of an existing suboptimal cooperative transmission (CT) routing protocol for wireless sensor networks, we formulate the lifetime-optimization problem using linear programming (LP), which requires considerations of CT's unique characteristics and sophisticated variable definitions. By evaluating LP for various cases, we show the effectiveness of cooperative routing by comparing it with the non-CT case. Also, by analyzing the LP solution, we identify some important factors and behaviors of optimal cooperative routing. More specifically, we conclude that (i) matching the rate of doing CT and matching the candidate pools of cooperators to the LP solution are important factors to achieve near-optimal lifetime performances, and, (ii) for small multi-hop networks, the design of cooperative routing can be simplified because one may use the sink node as a single VMISO receiver and rely on the existing energy-aware routing for the primary routing.**

***Index Terms*—Cooperative routing, lifetime-optimization problem, wireless sensor networks.**

I. Introduction

Cooperative transmission (CT) [1] is one way to improve the communication quality of single-antenna communication devices. A transmitting node that uses CT can share a data packet with neighboring single-antenna nodes, and then, the collection of these nodes can transmit the packet to an intended receiver, thereby creating a virtual multiple-input-single-output (VMISO) system. The intended receiving node can use physical-layer combining schemes to get diversity and array gains, which give CT a signal-to-noise ratio (SNR) advantage over the traditional single-input-single-output (SISO) case. CT's SNR advantage can be used to reduce the transmit powers of transmitting nodes, and this CT power-saving strategy has been shown by some authors to increase the lifetime of the network [2], [3], [4], [5]. However, when the circuit energy consumption of a node is comparable to its radiated energy, which is the case for popular sensor radios today [6], the power-saving strategy of CT cannot significantly reduce the overall energy consumption [7]. Therefore, CT power reduction alone is not always appropriate for maximizing the network lifetime.

Using CT's SNR advantage to extend the communication range in multi-hop wireless networks has also been studied [8], [9], [10], [11], [12]. The range-extension strategy of CT, which has been successfully demonstrated in [12], intentionally consumes more energy to extend the communication range, which provides more routing choices and reduced hops to the destination. In [11], we showed how the energy hole problem in multi-hop wireless sensor networks (WSNs) can be mitigated by using both the range-extension and power-saving CT. The energy hole forms in a non-CT network when all the nodes that are one SISO hop away from the sink node exhaust their energy because these nodes must relay all the packets from the rest of the network that are destined for the sink node [13]. In a CT network, range-extension CT can be used by the nodes that are two or more SISO hops away from the sink node to do one long VMISO hop directly to the sink node, and thereby relieve the one-SISO-hop-away nodes of their relaying burden and save their energy. By exercising range-extension CT selectively as an energy balancing tool and by reducing the transmit powers of the nodes doing CT so that only the minimum transmit power is used that is necessary to have a successful CT link to the sink node, network lifetime can be extended by factors of two or more, as shown by the REACT protocol in [11]. REACT mainly utilizes the range-extension CT, and it tries to use the transmit power that is necessary, and therefore, it can benefit from both the features of range extension and power reduction of CT, thereby providing the full benefit of cooperative routing. To our knowledge, no other works except [11] utilizes both features of CT to extend the lifetime.

Although the approach in [11] extends the network lifetime, it is not clear whether its lifetime performance and routing method are close to the optimal or not. That is, REACT first establishes a non-CT route (primary route) using an existing non-CT routing scheme, which may not always find an optimal path for cooperative routing. Also, in REACT, a node on the route triggers CT by comparing its residual energy with that of the next-hop node in its primary route. If the next-hop node has less energy, the node decides to do CT; it selects cooperators based on their residual energies and their distances to the sink node. Again, it is unclear that REACT's CT triggering and cooperator selection are providing an optimal way of

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using CT. Motivated by this fact, in this paper, we study the optimal lifetime and behavior of cooperative routing, which, to our knowledge, have never been theoretically analyzed. We also note that many CT-based routing works [2]-[4], [9] ignore the circuit energy consumption, which oversimplifies the problem or makes their approaches incorrect; in contrast, we try to correctly capture the energy cost of CT in our problem formulation.

For non-CT networks, the theoretical approach of the optimization of network lifetime when the transmit power control is possible is developed in [14]. The optimization problem that we want to solve for CT is more demanding because there are many more parameters in a VMISO link than there are in a SISO link. For instance, to specify a VMISO link, one must determine the number of cooperators and exactly which nodes will be the cooperators. Since all these parameters impact the energy consumption of a VMISO link, they all must be taken into account to optimize the lifetime of a multi-hop network.

By considering some unique characteristics of CT, we formulate a linear programming (LP) problem that can successfully capture the lifetime optimality of cooperative routing, which requires more sophisticated formulations than the case of non-CT. The LP solutions obtained from our formulation give the maximum achievable lifetime values of cooperative routing, and these values can be used as benchmarks to compare to the lifetimes of any cooperative-routing protocols. We use this fact to compare the optimal lifetime of CT with that of non-CT and the lifetime of an existing cooperative-routing protocol. Also, through evaluating/analyzing the LP solutions and performing network simulations for various cases, we identify important design parameters for the optimal cooperative-routing protocol, which can help simplify the overall protocol design.

Our paper is organized as follows. We formulate the lifetime-optimization problem of cooperative routing in Section II. The evaluations of the problem formulation and network simulations for various cases are done in Section III. In Section III, we also analyze our LP solution to determine the key routing behaviors of cooperative routing, and concluding remarks are offered in Section IV.

II. Problem Formulation

We formulate the lifetime-optimization problem for cooperative routing under the following assumptions. We consider a single-commodity[1] multi-hop wireless sensor network where sensed data is gathered at sink nodes, which are not energy constrained. Each node can be a source except for the sink nodes, and the data generated by a source node is forwarded to one of the sink nodes. For both non-CT and CT networks, data aggregation, compression, and network coding are not considered. We also adopt some of implicit assumptions of [14], such as collision is avoided so that no retransmission occurs, for our problem formulation.

We define the lifetime, T, of the network to be the time that the first node dies; this definition is widely used in the literature [15], [14], [16][2]. In Section II-C, we will explain how, under our assumptions, T is equivalent to another notion of lifetime, specifically, the total number of packets delivered to the sink nodes. We let A be the set of all nodes in the network, S_i be the set of neighbors of Node i, D be the set of destination nodes, and E be the set of nodes that are not energy constrained. In our formulation, D is the set of sink nodes, and $D \subset E$. We define e_{ij}^{TX} as the required energy for Node i to transmit a data unit from Node i to Node j, e_{ji}^{RX} as the required energy for Node i to receive a data unit coming from Node j, Q_i as the information generation rate (data/time) of Node i, and E_i as the initial energy of Node i. Since e_{ji}^{RX} is just circuit energy consumption, we use e^{RX} for the receiving energy instead of e_{ji}^{RX}.

In the case of non-CT, the lifetime-optimization problem can be formulated using LP as follows [14] (where a network is modeled as a directed graph):

Maximize T

$$\text{s.t. } n_{ij} \geq 0, \qquad \forall i \in A, \forall j \in S_i, \quad (1)$$

$$\sum_{j \in S_i} e_{ij}^{\mathrm{TX}} \cdot n_{ij} + \sum_{j : i \in S_j} e^{\mathrm{RX}} \cdot n_{ji} \leq E_i, \ \forall i \in A - E, \quad (2)$$

$$\sum_{j : i \in S_j} n_{ji} + T \cdot Q_i = \sum_{j \in S_i} n_{ij}, \qquad \forall i \in A - D, \quad (3)$$

where n_{ij} is the total number of data units transmitted from Node i to Node j until the lifetime T of the network, and $T \cdot Q_i$ is the number of data units generated by Node i during the lifetime of the network. (2) indicates the energy-constraint condition of Node i, and (3) is the data-conservation (flow-conservation) condition of Node i (we are directly looking at the amount of data instead of flows). Instead of the terms "energy-constraint condition" and "data-conservation condition," we use the abbreviated terms Cond-EC and Cond-DC, respectively. Note that the work in [14] (and also our work developed in this paper) relies on the fact that one can successfully define a link between two nodes. In [14], deterministic links are mainly used, and we discuss how one can apply our optimization problem for deterministic or random channels in Section II-C.

We use the following terms and conditions for the optimization problem of CT. A node, when it has a data to be transmitted, can either do CT by cooperating with its selected neighbors or do non-CT by sending its data to one of its neighbors. Neighbors of a node are the ones that are within SISO (non-CT) communication range of the node, and cooperators of a node are the neighbors of the node that are selected by the node to do CT. If a node decides to do CT (referred to as "triggering CT" in [11]), it becomes a CT initiator (or just an "initiator"), and it first sends its data to selected cooperators in the "CT sharing" or "multicast" phase. Next, the node (initiator) performs CT in the "CT phase" with the selected cooperators to send the data to the VMISO receiver through a VMISO link (for the initiator and cooperators, doing CT in the CT phase is the highest priority task). In the CT phase, the initiator and its cooperators transmit

[1] Here, "single commodity" means that, when there are multiple sink nodes, a source node needs only to send its data to one of the sink nodes (a "single" destination).

[2] For practical energy-balancing routing protocols, we observed that T is very close to the time of last node death [11], and in that case, T will closely approximate lifetimes of other definitions.

data to the VMISO receiver using orthogonal channels. The cooperators, which receive multicast (CT sharing) messages from an initiator, do CT with the initiator. Nodes can adjust their transmit power. A VMISO link can be formed between the 'cooperating nodes' (this term is different from the word cooperators because it includes cooperators and the initiator) and any node. Note that the maximum number of cooperating nodes, denoted by $N_c^{\max}$, cannot exceed the maximum number of orthogonal diversity channels. The initiator can select up to $N_c^{\max} - 1$ cooperators.

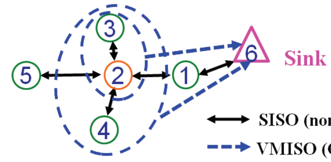


Fig. 1. A network example. Node 2 can form a VMISO link between itself and Node 6 (sink node) by cooperating with i) Node 3 or ii) Nodes 3 and 4. Node 3 can also form a VMISO to Node 6 by cooperating with Node 2. $N_c^{\max}$=3.

A. Intermediate Variables for CT

In this section, we define a set of intermediate variables, which capture the different ways of transmitting and receiving data in a CT-based network. These ways must be distinguished because they correspond to different values of energy consumption. In the next section, these intermediate variables will be expressed in terms of LP variables.

In a CT-based network, data can arrive at a node in different ways. It can be received over a SISO link from either a non-CT transmitter or from an initiator in the multicast (CT sharing) phase. Alternatively, it can arrive from a VMISO link or be self-generated. We denote the numbers of incoming data units arriving to Node i in each of these four ways by I_i^{n}, I_i^{m}, I_i^{v}, and I_i^{g}, respectively. Similarly, data can leave a node in different ways. It can be transmitted over a SISO link as either a non-CT transmission or from an initiator in the multicast (CT sharing) phase of CT. Alternatively, the data can be transmitted over a VMISO transmission by a node, which can be either an initiator or a cooperator (non-initiator). We denote the numbers of outgoing data units from Node i in each of these three categories by O_i^{n}, O_i^{m}, and O_i^{v}, respectively. Here, O_i^{v} encompasses two cases where (i) Node i initiates and does CT and (ii) Node i has received a multicast (CT sharing) message from its neighboring initiator and does CT, which corresponds to I_i^{m}. Note that if Node i initiates x CT instances, then Node i will multicast x times (O_i^{m}=x) and x CTs, and therefore, the number of outgoing CT (VMISO) data from Node i initiated by Node i is equal to O_i^{m}. Therefore, the following holds:

$$O_i^{\mathrm{v}} = O_i^{\mathrm{m}} + I_i^{\mathrm{m}}. \tag{4}$$

B. Optimization Problem Formulation for CT

In this section, we define LP variables for CT and formulate the optimization problem using the variables. In our LP formulation, as in [17], we explain our problem in terms of data packets, for convenience. However, the formulation can be explained in terms of bits or any other unit of data. For the remainder of this section, when necessary, we use the network in Fig. 1 where solid lines indicate SISO links and dashed lines indicate the VMISO links.

We first discuss why new LP variables are required for CT. Unlike the non-CT network, the energy consumption of a VMISO link between the initiator and a VMISO receiver highly depends on the combination of cooperating nodes. That is, as discussed in [11], when transmit power control for CT is possible, the minimum required transmit power to successfully reach the VMISO receiver depends on the combination of cooperating nodes. Also, the energy consumption of the initiator for data sharing (multicast) depends on how it selects its cooperators (it only needs to reach all its cooperators). Therefore, we need to define the new LP variables for CT that can represent the number of CT sharing messages from Node i to Node j for each possible combination of cooperating nodes.

We now define the new LP variables for CT. Let us denote by $R_{i,v}^N$, the set of N-tuples, $(r_1, r_2, ..., r_N)$, where $r_m \in S_i$ $(1 \leq m \leq N)$ and each tuple indicates the combination of cooperators that can reach Node v (a VMISO receiver) directly by cooperating with the initiator, Node i. For the example in Fig. 1, $R_{2,6}^1$={(3)}, $R_{3,6}^1$={(2)}, and $R_{2,6}^2$={(3, 4)}. Note that, given v, there can be $N_c^{\max} - 1$ different $R_{i,v}^N$'s for Node i (in other words, $1 \leq N \leq N_c^{\max} - 1$). Now, let $n_{i,v,j}^{N,k}$ be the number of CT sharing data from Node i to Node j that is related to the k-th tuple in $R_{i,v}^N$, denoted by $R_{i,v}^{N,k}$. For example, when $R_{2,6}^2 = \{(3,4),(3,5)\}$, we can define variables $n_{2,6,3}^{2,1}$ and $n_{2,6,4}^{2,1}$ that are related to the first tuple (3,4), $R_{2,6}^{2,1}$, and variables $n_{2,6,3}^{2,2}$ and $n_{2,6,5}^{2,2}$ are related to the second tuple (3,5), $R_{2,6}^{2,2}$. In this example, even though $n_{2,6,3}^{2,1}$ and $n_{2,6,3}^{2,2}$ both correspond to SISO communication from Node 2 to Node 3, they are two distinct LP variables for CT. In addition to these variables, if we define $n_{i,j}^{\mathrm{nCT}}$ as the number of data units transmitted from Node i to Node j using non-CT ($n_{i,j}^{\mathrm{nCT}}$ matches with n_{ij} of the non-CT LP formulation), we also have the variable $n_{2,3}^{\mathrm{nCT}}$ for the link between Node 2 and Node 3. Therefore, unlike the non-CT case, which requires a single variable n_{ij} for one SISO link from i to j, the LP formulation for CT has multiple variables defined for one SISO link. With $n_{i,v,j}^{N,k}$, we can correctly form Cond-EC for CT.

Given $R_{i,v}^N$ and fixed k, the following equality should hold for $j_m \in R_{i,v}^{N,k}$ $(1 \leq m \leq N)$ because CT sharing messages from Node i are multicast:

$$n_{i,v,j_1}^{N,k} = n_{i,v,j_2}^{N,k} = ... = n_{i,v,j_N}^{N,k}. \tag{5}$$

Now, we express the variables I's and O's in terms of the LP variables. For fixed v and N, the total number of outgoing data packets from Node i for the data sharing of CT is $\left(\sum_{j\in S_i} \sum_{k:j\in R_{i,v}^{N,k}} n_{i,v,j}^{N,k}\right)/N$. The reason why the denominator N is required is because the data sharing is multicast so that $n_{i,v,j}^{N,k}$ for a fixed k cannot be considered as N different instances. Since $\left(\sum_{j\in S_i} \sum_{k:j\in R_{i,v}^{N,k}} n_{i,v,j}^{N,k}\right)/N$ is for fixed v and N, we get O_i^{m} as follows:

$$O_i^{\mathrm{m}} = \sum_{N=1}^{N_c^{\max}-1} \left\{ \left(\sum_{v:v\in A-i} \sum_{j\in S_i} \sum_{k:j\in R_{i,v}^{N,k}} n_{i,v,j}^{N,k} \right) / N \right\}. \tag{6}$$

Also,

$$I_i^{\mathrm{m}} = \sum_{N=1}^{N_c^{\max}-1} \Big(\sum_{j:i\in S_j} \sum_{v:v\in A-j} \sum_{k:i\in R_{j,v}^{N,k}} n_{j,v,i}^{N,k} \Big). \qquad (7)$$

To formulate I_i^{v}, let us consider the case in Fig. 1 and assume that Node 2 transmits one packet to Node 6 by cooperating with Nodes 3 and 4. Each of three nodes (Nodes 2-4) sends the same packet to Node 6, and total three data packets are sent for this VMISO communication. However, these packets are combined to be one packet at the sink node. Note that when Node 2 initiates x CT instances, Node 6 receives x packets regardless of how Node 2 selects its cooperators. This means that I_i^{v} of some Node i (e.g., Node 6 in Fig. 1) can be obtained from the number of outgoing CT packets "initiated" by some Node h (e.g., Node 2 in Fig. 1). Since the number of outgoing CT packets "initiated" by Node h is equal to O_h^{m}, we can formulate I_i^{v} by (i) getting O_h^{m} for a fixed VMISO receiver i (using (6)) and (ii) using the fact that Node h can be any node except for the destination nodes and Node i, which results in

$$I_i^{\mathrm{v}} = \sum_{h:h\in A-D-i} \sum_{N=1}^{N_c^{\max}-1} \Big\{ \big(\sum_{j\in S_h} \sum_{k:j\in R_{h,i}^{N,k}} n_{h,i,j}^{N,k} \big)/N \Big\}. \qquad (8)$$

For I_i^{n}, I_i^{g}, and O_i^{n}, we can simply use (3) and get

$$I_i^{\mathrm{n}} = \sum_{j:i\in S_j} n_{j,i}^{\mathrm{nCT}}, \quad I_i^{\mathrm{g}} = T \cdot Q_i, \quad O_i^{\mathrm{n}} = \sum_{j\in S_i} n_{i,j}^{\mathrm{nCT}}. \qquad (9)$$

Let us consider Cond-DC for CT. In the case of CT, all incoming packets of Node i are transmitted to receiving nodes using either VMISO links or SISO links. Note that O_i^{m} is counting the packets for CT sharing, which is just an intermediate step to do CT and not the transmission to the intended receiver. Because of this, the sum of all incoming data packets should be equal to $O_i^{\mathrm{n}}+O_i^{\mathrm{v}}$ (not $O_i^{\mathrm{n}}+O_i^{\mathrm{m}}+O_i^{\mathrm{v}}$), which leads to the following Cond-DC of Node i for CT: $I_i^{\mathrm{n}} + I_i^{\mathrm{m}} + I_i^{\mathrm{v}} + I_i^{\mathrm{g}} = O_i^{\mathrm{n}} + O_i^{\mathrm{v}}$, or, using (4), $I_i^{\mathrm{n}} + I_i^{\mathrm{v}} + I_i^{\mathrm{g}} = O_i^{\mathrm{n}} + O_i^{\mathrm{m}}$.

Now, we formulate Cond-EC for CT. Note that the energy consumptions related to I_i^{n}, I_i^{m}, I_i^{v}, I_i^{g}, O_i^{n}, O_i^{m}, and O_i^{v} should all be considered for Cond-EC. The receiving energy consumption of SISO communication is e^{RX}, and it applies to I_i^{n} and I_i^{m}. The energy consumption of receiving CT packets depends on the number of cooperators, N_c (=N+1). For example, when the orthogonal diversity channel is obtained by using different time slots, a receiver has to spend more energy for VMISO reception than SISO reception because it has to receive all N_c packets. Therefore, if we define the energy consumption of receiving a CT packet (a CT data unit in general) when n cooperating nodes are transmitting as e_n^{RX}, the energy consumption related to I_i^{v} is

$$\sum_{h:h\in A-D-i} \sum_{N=1}^{N_c^{\max}-1} \Big\{ \Big(\sum_{j\in S_h} \sum_{k:j\in R_{h,i}^{N,k}} n_{h,i,j}^{N,k} \Big) \cdot \frac{e_{N+1}^{\mathrm{RX}}}{N} \Big\}. \qquad (10)$$

For the transmit energy consumption, we define $e_{i,v}^{N,k}$ as the required transmit energy for Node i to send a data unit to Node v (VMISO receiver) when all elements (nodes) of $R_{i,v}^{N,k}$ and Node i cooperate. Also, we denote the required transmit energy for Node i to multicast a data unit to all nodes that are elements of $R_{i,v}^{N,k}$ by $E_{i,v}^{N,k}$. O_i^{v} is related to CT packets that are either initiated by Node i (related to O_i^{m}) or initiated by neighbors of Node i that Node i needs to cooperate (related to I_i^{m}). Note that when CT is initiated by one of Node i's neighbors, j, Node i has to use $e_{j,v}^{N,k}$ because the energy cost for doing CT depends on how Node j selects the rest of cooperators. Therefore, the energy consumption related to O_i^{v} is shown in (11) and (12) at the top of the next page. e_{ij}^{TX} and $E_{i,v}^{N,k}$ are related to O_i^{n} and O_i^{m} respectively, and the energy consumption related to I_i^{g} can be expressed using the energy consumption for generating a data unit, denoted by e_i^{gen} (which is mostly the energy consumption for sensing in the case of the sensor network and is ignored in [14] and [17]). Cond-EC for Node i states that the total energy consumption of Node i should be less than or equal to its initial energy, and we can finally get the LP formulation for CT, which is summarized in Table I.

When LP variables related to CT ($n_{i,v,j}^{N,k}$'s) are ignored, the LP formulation of CT in Table I becomes that of the non-CT. Also, (5) can reduce the number of required LP variables. Sink nodes require neither Cond-EC nor Cond-DC, and the number of packets that reach a sink node d can be calculated by I_d^{n}+I_d^{v}.

C. Discussions: Assumptions and Usage of LP

Here, we discuss some of the practical issues of networks and how they relate to our problem formulation. Specifically, we address collisions, defining links, and the how the network lifetime T is related to the the number of packets delivered to the sink nodes.

Collisions. As in [14], our LP formulation is best suited for the cases where the collisions are minimal. Much research has been done for collision-free communication in WSNs, and the most widely used approach is to use TDMA-based scheduling [18], [19]. Also, for periodic and low data rate reporting applications, since the data traffic and volume are predictable, it is easy to schedule each node's transmission so that there exists one flow at a time [20], [21]. We note that even if there exist collisions in the network, our LP formulation still fulfills the overall objective; that is, the LP method can still give the ideal (no collision) upper bound on the lifetime performance.

Link Definitions. The LP variables in our problem formulation depend on how one defines a link, and the LP formulation requires the energy consumption of nodes associated with each link. In the case of power-saving CT, a VMISO link is formed between SISO neighbors (in other words, a node's SISO neighbor becomes a VMISO receiver). Given target error requirement and physical-layer characteristics (modulation, fading channel, path loss, etc.), a SISO link can be defined accordingly, and many power-saving CT works try to determine and use the amount of required transmit power for successful SISO and VMISO communications [4], [5], [22]. We note that one of the earlier works that address the required transmit power (and thus the energy consumption) for

TABLE I
LP FOR CT.

Maximize T

$$\text{s.t. } n^{\text{nCT}}_{i,j} \geq 0, \qquad \forall i \in A, \forall j \in S_i$$

$$n^{N,k}_{i,v,j_1} = n^{N,k}_{i,v,j_2} = \ldots = n^{N,k}_{i,v,j_N} \geq 0, \qquad \forall i, v \in A, i \neq v, R^N_{i,v} \neq \{\}$$

$$\sum_{j:i\in S_j} n^{\text{nCT}}_{ji} + T\cdot Q_i + \sum_{h:h\in A-D-i} \sum_{N=1}^{N_c^{\max}-1} \left\{ \Big(\sum_{j\in S_h} \sum_{k:j\in R^{N,k}_{h,i}} n^{N,k}_{h,i,j} \Big)/N \right\} = \sum_{j\in S_i} n^{\text{nCT}}_{ij} + \sum_{N=1}^{N_c^{\max}-1} \left\{ \Big(\sum_{v:v\in A-i} \sum_{j\in S_i} \sum_{k:j\in R^{N,k}_{i,v}} n^{N,k}_{i,v,j} \Big)/N \right\}, \qquad \forall i \in A - D$$

$$\sum_{j:i\in S_j} n^{\text{nCT}}_{j,i} e^{\text{RX}} + \sum_{j\in S_i} n^{\text{nCT}}_{i,j} e^{\text{TX}}_{ij} + (TQ_i) e^{\text{gen}}_i + \sum_{N=1}^{N_c^{\max}-1} \Bigg\{ \sum_{j:i\in S_j} \sum_{v:v\in A-j} \sum_{k:i\in R^{N,k}_{j,v}} n^{N,k}_{j,v,i} \cdot (e^{N,k}_{j,v} + e^{\text{RX}}) + \sum_{v:v\in A-i} \sum_{j\in S_i} \sum_{k:j\in R^{N,k}_{i,v}} n^{N,k}_{i,v,j} \cdot (e^{N,k}_{i,v} + E^{N,k}_{i,v})/N + \sum_{h:h\in A-D-i} \Big(\sum_{j\in S_h} \sum_{k:j\in R^{N,k}_{h,i}} n^{N,k}_{h,i,j} \Big) \cdot e^{\text{RX}}_{N+1}/N \Bigg\} \leq E_i, \qquad \forall i \in A - E$$

$$\sum_{N=1}^{N_c^{\max}-1} \left\{ \sum_{v:v\in A-i} \sum_{j\in S_i} \sum_{k:j\in R^{N,k}_{i,v}} \left(n^{N,k}_{i,v,j} \cdot e^{N,k}_{i,v} \right)/N + \sum_{j:i\in S_j} \sum_{v:v\in A-j} \sum_{k:i\in R^{N,k}_{j,v}} \left(n^{N,k}_{j,v,i} \cdot e^{N,k}_{j,v} \right) \right\}. \tag{11}$$

$$\sum_{N=1}^{N_c^{\max}-1} \left\{ \sum_{v:v\in A-i} \sum_{j\in S_i} \sum_{k:j\in R^{N,k}_{i,v}} \left(n^{N,k}_{i,v,j} \cdot e^{N,k}_{i,v} \right)/N + \sum_{j:i\in S_j} \sum_{v:v\in A-j} \sum_{k:i\in R^{N,k}_{j,v}} \left(n^{N,k}_{j,v,i} \cdot e^{N,k}_{j,v} \right) \right\}. \tag{12}$$

successful VMISO and SISO communications is [7], which obtains the required energy per bit through either approximation (based on the Chernoff bound) or channel realizations (Monte Carlo simulations). Although these different CT works ([7], [4], [5], [22], etc.) use different assumptions, models, and energy consumptions, what these works have in common is that all physical-layer characteristics between a link can be merged into one parameter: energy per bit. This indicates that our LP formulation is able to handle different physical-layer characteristics and assumptions because the energy consumption of nodes associated with each link is what we use for our LP formulation. In the case of range-extension CT, extended VMISO links exist, and one way to obtain possible extended VMISO links when cooperating nodes are given is presented in [11], where, similar to power-saving CT, physical-layer characteristics (except for path loss) are merged into one parameter: diversity gain. This concept has been originally presented in [8], and, in [21], the path loss characteristic in a particular building [12] is used and the diversity gain is obtained using Monte Carlo simulation. Regardless of whether one is using power-CT or range-extension CT, as long as one can define a link and obtain the energy consumption associated with the link, one can formulate the optimization problem using our LP approach.

We note that many lifetime-extension CT works implicitly ignore retransmissions as in our LP formulation; either the required transmit power (or energy per bit) is considered to be enough for a successful communication [4], [5], [22] or the channel condition is assumed to known at the transmitting node(s) so that power control can be done appropriately to achieve a successful communication (conforming to a target error requirement) [2] [3]. However, if one wishes to analyze the optimal lifetime considering lossy links, which have decoding errors and retransmissions from time to time, it is not impossible to do it with our LP; again, one just needs to determine the energy consumption associated with lossy links. The work in [23] presents a possible approach for such a case by introducing transmission count, which is defined as the expected number of transmissions needed for a node to successfully send a packet to its receiver. One could get the required energy per bit for a given link considering the transmission count, which could in turn be used in our LP formulation. The transmission count of a link can be estimated based on the physical or empirical model of the radio or using a link estimator [23], and more elaboration may be required to define lossy links. The main contribution of this paper is the LP formulation, and modeling the energy consumption for lossy links is out of scope of this paper.

Lifetime. In our formulation, lifetime, T, has units of time, and T can be related to the number of packets received by sink nodes as follows. First of all, because of the data conservation condition, all the packets received by a node should be transmitted. The sink nodes, however, are not constrained by this condition because they are destinations (no need to transmit), so in our LP formulation, all generated packets end up in sink nodes. Note that a practical scenario where a node may die after receiving a packet so that the node has no chance of transmitting its received packet (has data in its buffer when dies) is not captured in our LP formulation because of Cond-DC (in other words, because of Cond-DC, all generated packets reaches the sink node in our LP formulation). However, the scenario (where a node dies failing to send its packet to the destination) is no different from the case where Cond-DC is preserved if we are looking at the number of packets received by sink nodes, which is also a widely used definition of lifetime [15], [24], [11] (undelivered packets wouldn't be counted toward "lifetime"). Note that, from the discussion above, the number of packets received by sink nodes should be equal to the total number of packets generated by nodes, which is $\sum_i T \cdot Q_i$. When Q_i is given, maximizing T is exactly the same as maximizing $\sum_i T \cdot Q_i$, which is the total number of packets generated by nodes, and therefore, our LP formulation inherently maximizes the number of packets received by sink nodes. Since T is the lifetime of the "first" node's death, we can compare the lifetime performance of a routing protocol with the optimal lifetime value obtained from LP by getting the number of received packets by sink nodes using network simulations till the first node dies.

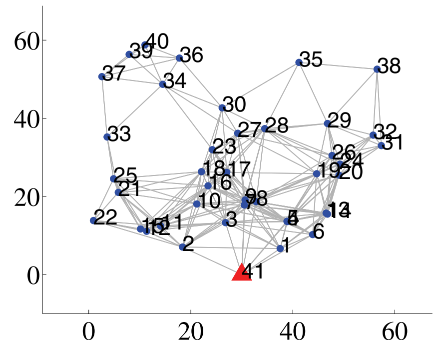


Fig. 2. One sample topology of 60m×60m networks (solid lines indicate SISO links).

III. Evaluation and Analysis

In this section, we formulate and solve the LP equations derived in Section II for given network models, and we analyze the LP results. As mentioned in the previous section, there are many different ways to model links and channels, and evaluating our LP for many possible link definitions and physical-layer approaches/assumptions is out of scope of this paper.

A. Simulation Models and Parameters

We consider multi-hop networks having a sink node with no energy constraint. All nodes have the same maximum transmission range of 20m ($d_{\text{tx}}^{\text{max}}$=20m), and a SISO link exists from Node i to Node j if Node j is within $d_{\text{tx}}^{\text{max}}$ from Node i. This makes SISO links deterministic. The LP solution[3] can provide the optimal lifetime bound of cooperative routing, and, to see the usefulness of this bound more clearly, we also perform network simulations for REACT in [11] and compare its lifetime performance with the optimal case, under the same assumptions as our LP formulation, of no collisions or packet loss. Since we compare the results of REACT with our LP results, we adopt some of the features of [11]. In [11], the possibility of reaching a certain destination using CT (and the power control of CT as well) is determined through d_{req}=$(10^G \cdot \sum_{i=1}^{N_c} d_{i,v}^{-\alpha})^{-1/\alpha}$ where G is the diversity gain in dB, α is the path loss exponent, and $d_{i,v}$ is the distance between i-th cooperating node and a VMISO receiver, Node v. To be more specific, in order for cooperators to reach the destination, the following condition should hold:

$$d_{\text{req}} \leq d_{\text{tx}}^{\text{max}}. \tag{13}$$

We use d_{req} in [11] for creating the set $R_{i,v}^N$ for Node i. That is, for Node i and Node v, we first fix N and consider each combination of Node i's cooperators and calculate d_{req}, and if (13) holds, we add the combination to $R_{i,v}^N$. We do this procedure for all possible N's ($1 \leq N \leq N_c^{\text{max}} - 1$) and get the complete set of $R_{i,v}^N$. Based on $R_{i,v}^N$, the LP variables for CT are defined. We also use d_{req} to get $e_{i,v}^{N,k}$. That is, $e_{i,v}^{N,k}$ = 'circuit energy consumption' + 'radiated energy consumption required to reach d_{req}.' When calculating d_{req}, we use the path loss exponent of 2.9 and cooperative diversity gains in [21] obtained from assuming Rayleigh fading, log-normal shadowing with the shadowing standard deviation of 5dB, BPSK modulation, and a target bit error rate of 10^{-3}. We obtain the LP results by considering the *data packet* flows of the network, which makes the LP variables $n_{i,j}^{\text{nCT}}$ and $n_{i,v,j}^{N,k}$ the total number of "data packets" transmitted by Node i. We use the energy model in [13], which has transmit circuit energy of 45nJ/bit and receive circuit energy of 135nJ/bit, and assume 128 bytes of data. We do not consider the energy consumption for generating data ($e_{i,\text{gen}}$=0), and $E_{i,v}^{N,k}$=max$(e_{ij_1}^{\text{TX}}, e_{ij_2}^{\text{TX}}, ..., e_{ij_M}^{\text{TX}})$ where $j_1, j_2, ...j_M$ are the elements of $R_{i,v}^{N,k}$. We measure the lifetime performance in terms of the number of packets that successfully reach sink nodes. Since $n_{i,v,j}^{N,k}$ and $n_{i,j}^{\text{nCT}}$ are integers, we formulate and solve a mixed-integer LP problem. When solving LP, we use GNU LP Kit (GLPK) [25], which can give the optimal value of T and the values for LP variables (n's) once LP is correctly formulated following Table I.

The orthogonal diversity channel is obtained by space-time block code (STBC) [26], and the maximum number of orthogonal channels is three (N_c^{max}=3). Note that when STBC is used, each CT packet in the CT phase is encoded using an appropriate space-time code [10]. Also, for STBC with the diversity order of three, the best achievable rate is 3/4, which increases the energy consumption of doing CT for N_c=3, and the increased energy consumption is taken into account (as in [22]). All nodes have the initial energy of 50mJ. Each node has identical data generation rate, and we set Q_i=1. Note that the conditions and assumptions made so far are for "our" evaluation purpose. One can use different link definitions, physical-layer characteristics, energy-consumption models, traffic models, etc. to evaluate one's own particular situation using the LP formulation derived in Section II.

We consider square-shaped networks with a single sink node located at the bottom center of the network. There are 40 nodes in the network (excluding the sink node), and nodes are randomly deployed except for the sink node. One sample topology of 60m×60m networks is shown in Fig. 2. For each size of network, 20 trials are performed (for both LP and the network simulations), and, in each trial, nodes are randomly relocated except for the sink node. For network simulations, we assume that sensing tasks are well scheduled so that there is only one flow at a time.

[3]Note that, in LP, every local maximum is a global maximum.

For simulating cooperative-routing protocols such as REACT, we run network simulations to get the number of packets that reach the destination till one of the node dies (first node's death). Note that, in the case of LP, we form matrices and vectors, and the LP formulation can be solved using any LP solution method, whereas, in the network simulation, packets are sent from node to node following routing decisions, and we measure the lifetime in terms of the number of packets that the destination receives. When simulating cooperative routing, as in [11], we consider two non-CT primary routing schemes: i) Ad hoc On-demand Distance Vector (AODV) [27] and ii) Capacity Maximization (CMAX) [15], which is an energy-aware routing scheme. We denote REACT using AODV by REACT-AODV and REACT using CMAX by REACT-CMAX.

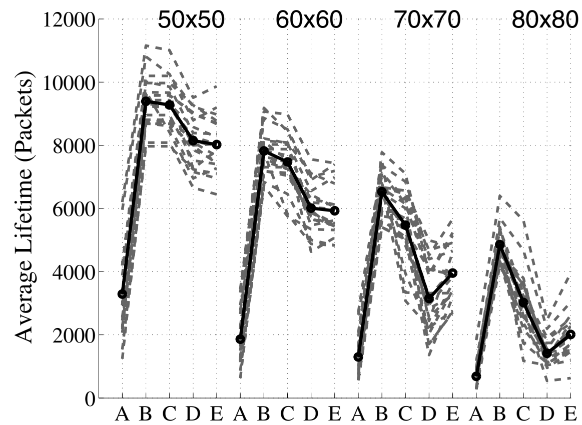


Fig. 3. Average lifetime performance of four different network sizes (50m×50m, 60m×60m, 70m×70m, and 80m×80m).

B. Optimal Network Lifetime of Cooperative Routing

In this section, we evaluate the optimal lifetime performances of cooperative routing, which can be obtained from the LP formulation in Section II. These values are very important not only because they indicate how powerful cooperative routing can be when compared with non-CT routing, but also because they can be used as a reference value when evaluating other cooperative-routing methods.

The work of [11] considers the case of forming a VMISO link between cooperating nodes and the sink node (we will refer to this as "VMISO-Sink"), which means that there is only one VMISO receiver in the network. To see the benefits of allowing VMISO reception for any node, referred to as "VMISO-Any," we consider both VMISO-Sink and VMISO-Any when formulating LP. Note that in the LP formulation of VMISO-Any, one needs to consider e_n^{RX}, which does not need to be included for VMISO-Sink.

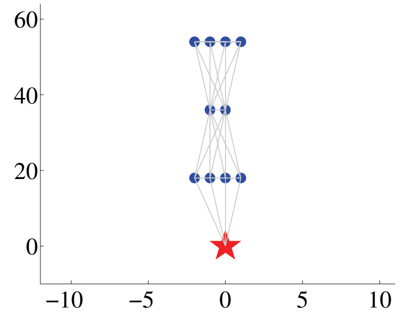
In Fig. 3, the average lifetime performances (in terms of the number of packets) of four square-shaped networks are shown. In the figure, A, B, C, D, and E indicate optimal non-CT, optimal VMISO-Any, optimal VMISO-Sink, REACT-AODV, and REACT-CMAX, respectively. Note that LP is used for A, B, and C, and the network simulation is used for D and E. The circled solid lines indicate the mean values, and each dashed line is the outcome of one sample trial. When viewing the outcomes of individual trials, we observe that the *relative* performance of the different schemes are highly correlated indicating the significant dependence of performance on topology, for any scheme. In other words, if Scheme A is better than Scheme B in one trial, A is very likely to be better than B in another trial. As can be seen from Fig. 3, the optimal lifetime performances of CT clearly outperform those of non-CT. Fig. 3 shows that VMISO-Any becomes notably better than VMISO-Sink when the network is large, and this is further discussed in Section III-C. It can also be seen that REACT's performance is higher than that of the optimal non-CT scheme, however, it is observed that there is a notable gap between the optimal lifetime of VMISO-Sink and the lifetime of REACT (REACT is a VMISO-Sink scheme) especially for larger networks, showing that REACT cannot be considered as performing optimally. The lifetime-optimization of cooperative routing, which uses VMISO links, gets more complicated as the network size grows because the increased number of hops from the sink node means that each sensed data may go through more than one CT decision (including whether to do CT or non-CT and selecting cooperators); all decisions need to be optimally made in order to maximize the network lifetime, and, because of the suboptimal methods of REACT, the lifetime of REACT deviates from the optimal as the network gets larger.

In summary, this section showed one important aspect of having the LP formulation for cooperative routing; it can determine whether a CT-based protocol behaves optimally or not, and one can determine the optimality of one's own cooperative-routing protocol using the LP formulation developed in Section II.

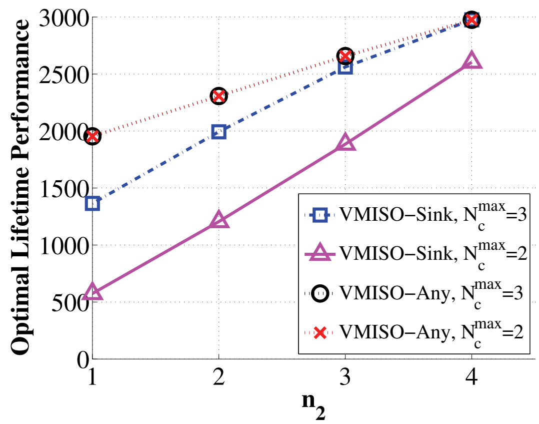
C. VMISO-Sink vs. VMISO-Any

This section discusses when and how VMISO-Any can be useful (one possible cross-layer framework for VMISO-Any is developed in [8]). It is clear that VMISO-Any can be advantageous over VMISO-Sink when it allows better energy usage compared to VMISO-Sink, and to explain those situations, we use simple 3-hop networks, one of which is illustrated in Fig. 4a. For this network, we refer to the nodes i hops away from the sink node as "i-hop nodes," and the total number of i-hop nodes in the network is denoted by n_i. Here, $n_1 = n_3 = 4$, and n_2 varies. Also, for this network, we consider the case where a SISO link can be established between any i-hop node and any (i+1)-hop node.

When n_2 is very small (like one or two), then 2-hop nodes are the bottleneck nodes, and they die earlier than the others for non-CT networks, and, in order to prolong their lifetimes using CT, 3-hop nodes can use range extension CT to reduce the relay burden of 2-hop nodes [11]. Note that, based on the model in Section III-A, VMISO-Sink requires at least three cooperating nodes to form a VMISO link from 3-hop nodes to the sink node, whereas, VMISO-Any has an additional option to form a VMISO link from 3-hop nodes to a 1-hop node using only two cooperating nodes, which can play an important role especially when 2-hop nodes are the bottlenecks. Moreover, if $N_c^{\max}$ is only allowed to be two, VMISO-Sink loses the option



(a) A simple 3-hop network (solid lines indicate SISO links). n_1=4, n_2=2, and n_3=4.



(b) Lifetime performance. n_1 and n_3 are four, and n_2 (x-axis) is varied.

Fig. 4. Comparisons of VMISO-Sink and VMISO-Any. Simple 3-hop networks.

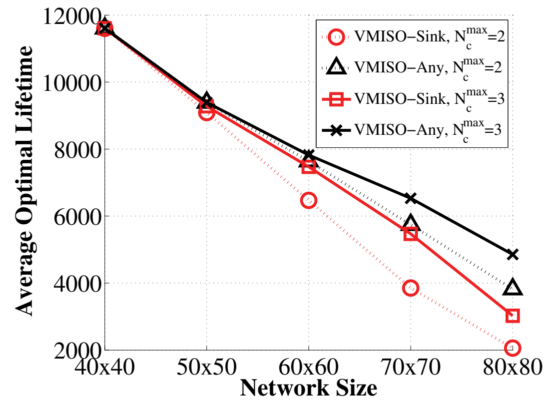


Fig. 5. Average optimal lifetime performance of VMISO-Sink and VMISO-Any. Random square-shaped topologies (20 different network topologies per a fixed network size).

of forming a VMISO link using 3-hop nodes, which critically harms its lifetime performance. Also, since two cooperating nodes are enough for VMISO-any to form a VMISO link from 3-hop nodes to a 1-hop node, it is expected that increasing $N_c^{\max}$ will have no impact on the lifetime performance of VMISO-Any. The results in Fig. 4b, which shows the optimal lifetimes of VMISO-Sink and VMISO-Any obtained from the LP formulation for $N_c^{\max}$=2 and 3, clarify the discussion made so far. We can see that two VMISO-Any cases are essentially identical as expected. When $N_c^{\max}$=3, VMISO-Sink approaches the performance of VMISO-Any as the bottleneck situation is resolved. However, when $N_c^{\max}$=2, it can be seen that the performance gap between VMISO-Sink and VMISO-Any is much worse than that of $N_c^{\max}$=3. This is because, for VMISO-Sink with $N_c^{\max}$=2, 3-hop nodes only does non-CT because three cooperating nodes are required to form a VMISO link to the sink node, and their energies cannot be fully utilized. Fig. 4b shows that the existence of nodes in the network that cannot form VMISO link directly to the sink impacts the performance gap between VMISO-Any and VMISO-Sink more than the existence of the bottleneck. The discussion so far explains why the optimal performance of VMISO-Sink deviates from that of VMISO-Any in Fig. 3 as the network area grows.

Fig. 5 compares the average optimal lifetime performances of VMISO-Any and VMISO-Sink for the square-shaped topologies (nodes are deployed randomly) defined in Section III-A when $N_c^{\max}$=2 and 3. As can be seen from the figure, for small multi-hop networks requiring a few number of hops to reach the sink node, since VMISO-Sink can form VMISO link directly to the sink node with two cooperating nodes most of the time, VMISO-Sink and VMISO-Any have almost identical performance regardless of $N_c^{\max}$. Note that using VMISO-Sink has the following advantages over VMISO-Any: (i) simpler protocol design because there is only one VMISO destination and (ii) simpler hardware for nodes other than the sink node because the diversity combining only needs to be done at the sink node, which makes VMISO-Sink more appropriate for simple WSNs than VMISO-Any. Also, having a smaller $N_c^{\max}$ simplifies the overall protocol because one needs to manage fewer orthogonal channels and fewer cooperators. Through the evaluation in this section, we have shown that reaching the near-optimal lifetime performance using VMISO-Sink with small $N_c^{\max}$ may be possible for small networks, which shows another usage of the LP formulation; one can determine (i) which VMISO scheme it should use and (ii) $N_c^{\max}$ for given network and conditions, which can be helpful in simplifying a protocol.

D. Analysis of LP: Protocol Design Considerations for Cooperative Routing

The LP formulation derived in Section II can also provide observations regarding the optimal protocol behaviors of cooperative routing, which are discussed in this section. We analyze the LP results to learn important factors that may help us understand and design a practical, near-optimal cooperative-routing protocol. Here, we focus on the VMISO-Sink case because it is better suited for simple WSNs.

Let us consider all non-zero LP results related to Node 30 obtained from the network in Fig. 2: $n^{\text{nCT}}_{30,18}$=9, $n^{\text{nCT}}_{30,27}$=57, $n^{\text{nCT}}_{36,30}$=150, $n^{1,1}_{30,41,17}$=221, and $n^{1,2}_{30,41,18}$=64. From these values, we can learn how Node 30 handles its packets when it decides to do non-CT or CT. That is, Node 30 transmits its packets to either 18 or 27 when it decides to do non-CT, and, when it decides to do CT, it uses only one cooperator (up to two cooperators are possible), and its cooperator is either Node 17 or 18. We denote the desirable cooperator groups for Node i

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that LP suggests by G_i (G_{30}= {{17},{18}})[4]. Therefore, from LP, we can learn the non-CT route behavior and cooperator selection for maximizing the lifetime of cooperative routing. However, how a node decides whether to do CT or non-CT is not clear (in REACT [11], decision of doing CT is triggered by comparing the residual energies of nodes). Note that we know how many packets Node 30 decides to do CT, which is 285 (=221+64), and using the fact that total 351 packets are transmitted by Node 30, we can get the ratio of doing CT for Node 30, which is 0.812 (=285/351). Suppose we denote the ratio of doing CT for Node i by r_i^{CT}, and r_i^{CT} could somehow be known a priori. Then, in a practical protocol, Node i can decide to do CT (trigger CT) to match r_i^{CT}, and one of the simple ways to do this is to generate a random number between 0 and 1 and decide to do CT when the random number is less than or equal to r_i^{CT} (there can be many ways to match the ratio, and generating a random number is just one of them; we were able to observe that this way can closely match the fixed ratio in a long run). Likewise, when Node i decides to do CT, it has the ratio of selecting k-th group of G_i, which will be denoted by $r_{i,k}^{\text{coop}}$, as its cooperator (for example, $r_{30,1}^{\text{coop}}$=221/285). Similarly, when Node i decides to do non-CT, it has the ratio of selecting Node k as its next hop, which will be denoted by $r_{i,k}^{\text{nCT}}$. Again, one of the simple ways to match $r_{i,k}^{\text{coop}}$ is to generate a random number between 0 and 1 and select k-th group of G_i when the random number is between $\sum_{a=0}^{k-1} r_{i,a}^{\text{coop}}$ and $\sum_{a=0}^{k} r_{i,a}^{\text{coop}}$ where $r_{i,0}^{\text{coop}}$=0 (Node i can match $r_{i,k}^{\text{nCT}}$ using a similar method). $r_{i,k}^{\text{nCT}}$ is related to the non-CT route, G_i and $r_{i,k}^{\text{coop}}$ are related to the cooperator selection, and r_i^{CT} is related to CT decision (CT triggering). We are particularly interested in whether the ratio of doing CT (r_i^{CT}) can be effective when used as CT triggering because, unlike the non-CT route and cooperator selection that involve selecting neighbors, it is just a fixed ratio for Node i. Any scheme that tries to match $r_{i,k}^{\text{nCT}}$, $r_{i,k}^{\text{coop}}$, and r_i^{CT} will be referred to as *pseudo-optimal* because those values are obtained from LP (optimal), but the scheme only tries to match the ratio and is energy-unaware (not exactly optimal). The non-CT routing that tries to match $r_{i,k}^{\text{nCT}}$ is referred to as pseudo-optimal routing (POR), and CT methods that try to match $r_{i,k}^{\text{coop}}$ and r_i^{CT} are referred to as pseudo-optimal cooperator selection (POCS) and pseudo-optimal triggering (POT), respectively.

We perform network simulations to compare these pseudo-optimal schemes to identify the important factors in cooperative routing. For the network simulation, we use three non-CT routing algorithms for the primary routing of CT: (i) AODV, (ii) CMAX, and (iii) POR. The simulation parameters are exactly the same as those used in Section III-B. We first see if POT can be useful in maximizing the lifetime. Fig. 6 shows the average lifetime results (over 20 trials), obtained from network simulations, for the 60×60 networks used in Section III-B. Fig. 6 is showing four different combinations of CT triggering and cooperator selection: (i) original REACT, (ii) POT and POCS, (iii) POT and REACT's cooperator selection, and (iv) REACT's CT triggering and POCS. The dashed horizontal line

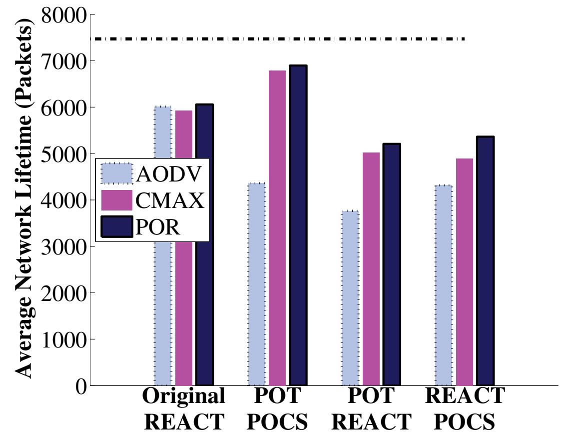

Fig. 6. Average network lifetime of 60×60 networks.

in the figure indicates the average optimal lifetime obtained from the LP solution. As can be seen from Fig. 6 (leftmost 3 bars), REACT with POR does not notably improve the performances of REACT-AODV and REACT-CMAX, which indicates that the primary routing scheme has little to do with the performance of REACT. When POT and POCS are used with POR or CMAX, it can be seen that the performance of the CT protocol improves greatly, and this means that the ratio of doing CT, when coupled with appropriate cooperator selections, can play an important role in extending the network lifetime. In other words, the ratio of doing CT can be one of possible decision criteria for doing CT. It is also evident that REACT's decision criterion (based on the residual energy comparison) is not so desirable. Also, as can be seen from Fig. 6, using POT alone (or using POCS alone) worsens the performance of the original REACT, which indicates that the ratio of doing CT and the cooperator selection should be jointly optimized.

Fig. 7 shows the average lifetime results for the four different networks that we have considered in Section III-B. Here, the average lifetime values are normalized by the optimal values obtained from LP. For the original REACT, Fig. 7 shows the one with the best performance (out of the three possible primary routing cases). Here, we do not provide the cases where POT and POCS are not jointly used because they always perform worse than the original REACT protocol. Instead, we put the cases of using G_i only instead of $r_{i,k}^{\text{coop}}$ for the cooperator selection, referred to as POCS2 (that is, only cooperating group information is used without matching the rate $r_{i,k}^{\text{coop}}$). In POCS2, we need another method of choosing one of the multiple cooperating groups, and we consider the case where a node selects a cooperating group that has the largest minimum residual energy. From the figure, it can be observed that POCS2 with POR performs better than POCS with POR, which indicates that having desirable cooperator groups (G_i) is good enough and matching $r_{i,k}^{\text{coop}}$ is not as important as applying energy-awareness to G_i. When POT and POCS (or POCS2) are used with CMAX, denoted by POT,POCS(or POCS2)-CMAX, for "smaller" networks, the lifetime performance is not so different from that of POT and POCS using POR (POT,POCS-POR), which is quite surprising

[4]The nodes far away from the sink node require more than one cooperator. For example, Node 38 in Fig. 2 has G_{38}= {{32, 35}, {31, 35}, {31, 32}, {29, 35}} according to the LP results.

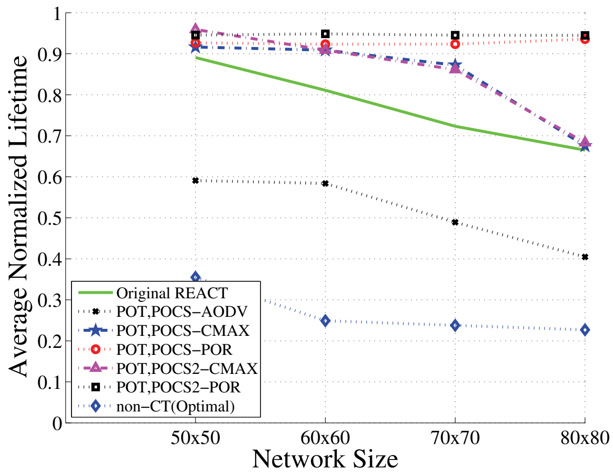

Fig. 7. Average normalized lifetime results.

considering the facts that (i) CMAX has nothing to do with LP results and (ii) $r_{i,k}^{\mathrm{nCT}}$ of Node i influences the energy consumption of Node i's neighbors. Since nodes in smaller networks are only a few hops away from the destination, there are not many routing choices, and the energy-aware routing schemes such as CMAX try to evenly distribute the energy consumption of nodes as much as possible. The LP solution tries to fully utilize each node's energy, which eventually balances the energy consumption of nodes, and this can be the reason why both POR and CMAX, when supported by pseudo-optimal CT behavior, perform very well for smaller networks. This is very important because it implies that, for small networks, one may rely on an existing energy-aware routing scheme as the primary routing scheme in CT-based network, which eases the protocol design because jointly optimizing the primary routing scheme and CT behavior is not necessary. For larger networks, the performance of POT,POCS(or POCS2)-CMAX degrades compared to POT,POCS-POR, which means that CMAX does not perform optimally with POT and POCS when the network is large[5].

In summary, we identified two important factors, the ratio of doing CT (r_i^{CT}) and desirable cooperator selections (G_i), that one may consider when designing an optimal cooperative-routing protocol, which may not need to be jointly optimized with the primary routing scheme for small networks. Note that, we have determined the values of G_i and r_i^{CT} using LP solutions, which must be computed "off-line" and require the data-generation rate to be known in advance. Whether one can design an online scheme[6] that can learn and use G_i and r_i^{CT} efficiently is an open question and is out of scope of this paper. If it is possible to determine G_i and r_i^{CT}, the protocol behavior of cooperative routing is straightforward; a node has to match r_i^{CT} for CT decision, and, when it decides to do CT, it uses one of cooperator groups in G_i to form VMISO.

[5]The same conclusion can be drawn when different number of nodes are used for four different network sizes, and those results are omitted.

[6]REACT and CMAX are online protocols that do not need to have the data generation rates in advance.

IV. Conclusion

In this paper, we studied the optimal lifetime and behaviors of the cooperative routing. Using LP, we formulated the lifetime-optimization problem for cooperative routing that allows transmit power control and variable numbers of co-operators, which requires considerations of CT's unique characteristics and sophisticated variable definitions. By solving LP for cooperative routing, the optimal network lifetimes of cooperative routing were obtained and compared with those of the non-CT case to show the non-trivial lifetime improvement that CT can theoretically achieve. Also, we showed the usefulness of our LP by comparing the optimal performance to that of an online cooperative-routing protocol through evaluations and simulations. We've also showed that allowing any node to be a VMISO receiver is not always necessary to achieve the optimal lifetime performance by providing the cases where allowing only the sink node to be a VMISO receiver is enough. We observed several key routing behaviors in the LP solutions, and, through testing protocols that approximate these behaviors, we determined certain factors that are important, which can be used when designing an optimal cooperative-routing protocol. For small multi-hop networks requiring a few number of hops to reach the sink node, we found that the design of cooperative routing can be simplified because one may use the sink node as a single VMISO receiver and rely on the existing energy-aware routing for the primary routing.

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